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High-power light-emitting diodes (LEDs) today are twice as powerful as four years ago while meantime their price has been divided by 4 making them promising sources for laser pumping. However, their irradiance still falls short by one order of magnitude of what is needed to efficiently pump solid-state lasers. We demonstrate that an LED-pumped Ce:YAG luminescent concentrator (LC) can increase the irradiance of blue LEDs by a factor of 10, with an optical efficiency of 25%, making them much more suitable to pump solid-state lasers. In our demonstration, we used 100 Hz pulsed LEDs emitting 190 W/cm^2 at 430 nm to illuminate a Ce:YAG LC, leading to an output irradiance of 1830 W/cm^2. The LC is used to pump a Nd:YVO$_4$ laser producing 360 μJ at 1064 nm, corresponding to an optical efficiency of 2.2% with respect to the LC. LED-pumped luminescent concentrators pave the way for high-power, low-cost, solid-state lasers.

OCIS codes: (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state; (220.1770) Concentrators; (230.3670) Light-emitting diodes.

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Solid-state lasers are typically devices that convert low-brightness pump light (e.g., from flashlamps or laser diodes) into a high-brightness laser beam. Controlling how efficiently the pump light is transferred to the gain medium is an essential part of laser design governing efficiency, threshold, and power scalability, and generally consists in maximizing the pump irradiance starting from a source with a given brightness.

The classical way to do so is to use geometrical concentration, based either on imaging or nonimaging optics [1]. Since the brightness is conserved in virtue of the brightness theorem [2], increasing irradiance goes along with altering the pump light directionality. Consequently, no irradiance enhancement is possible at all whenever the pump source is a Lambertian emitter, which is the case for light-emitting diodes (LEDs).

LEDs show, however, great promise for pumping solid-state lasers at low costs. While the first demonstration of LED pumping of laser materials goes back to 1964 [3], it has recently experienced a renewed interest driven by the spectacular development of LEDs for the lighting market. Thus, various LED-pumped laser media have been reported as follows: polymers [4], fibers [5], semiconductors [6], and more recently Nd-doped matrices [7,8].

Even though LED performance has been remarkably improved since the 1970s [9], the power densities of LEDs (typically 100 W/cm^2) are still several orders of magnitude lower than those attained with laser diodes. Because geometrical concentration cannot be used, the design of low-cost, efficient, and power-scalable LED-pumped laser systems requires novel design strategies.

The brightness conservation rule can be broken as far as the wavelength is changed, a principle at work in luminescent concentration. In this Letter, we use a luminescent concentrator (LC) to increase the irradiance of LEDs and make them suitable for efficient, low-cost, and power-scalable solid-state lasers.

LCs have been thoroughly studied for decades for harvesting solar energy in the context of photovoltaic energy production. A typical LC is a slab of a transparent material embedding fluorescent luminophores such as dyes, luminescent ions, or quantum dots. Those luminophores absorb the incident light through the large "pumped" areas and then emit lower-frequency light that is for a large part guided by total internal reflections (TIR) up to the small end surfaces, leading to an increase of the output irradiance directly related to the ratio between the large and small surface areas.

LCs have been widely used to collect sunlight and concentrate it onto solar cells [10], and also for greenhouse applications [11] or for indoor illumination [12]. However, in the context of laser pumping the requirement for an efficient LC is quite different, as the input source is more monochromatic and the output device (the laser) has narrow absorption bands and is sensitive to the irradiance at the output of the LC. To our best knowledge, LCs have been used only once for laser pumping, when Turnbull and co-workers illuminated an organic LC made of fluorescent dyes embedded in a polymer thin film with an optical parametric oscillator (to emulate LEDs), and then used it to pump a distributed feedback polymer laser [13].

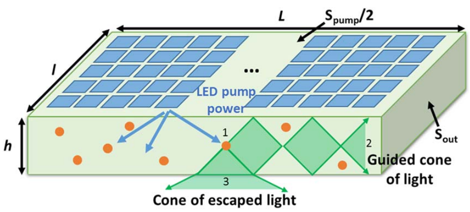

Fig. 1. Schematic representation of a light concentrator pumped by LEDs. (1) The pump light is absorbed by a luminophore. (2) The light is re-emitted and guided toward the edges of the LC by TIR. (3) A part of the re-emitted light escapes the LC and is lost.

In this Letter, we propose for the first time the experimental demonstration of a solid-state laser pumped by a luminescent concentrator illuminated by LEDs. As a proof of principle, we used $Nd:YVO_4$ as the laser medium and a robust crystalline LC made of Ce^{3+} ions in a YAG matrix.

The basic scheme of our LC is described in Fig. 1. It consists of an optically polished YAG slab (with dimensions $L \times l \times h$) doped by Ce^{3+} ions. LEDs are close coupled to the large faces of the slab ($S_{\mathrm{pump}} = 2L \times l$). The light re-emitted by the luminophores and guided by TIR is collected through the edge face S_{out} ($S_{\mathrm{out}} = l \times h$).

LC performance is generally described with the concentrator factor C defined as the ratio of the output to the input power densities (in $\mathrm{W/cm^2}$). With the given parameters, it can be written as the product of the geometrical concentration factor G (which equals $S_{\mathrm{pump}}/S_{\mathrm{out}}$) by the optical efficiency $\eta_{o/o}$:

$$C = \frac{I_{\mathrm{out}}}{I_{\mathrm{pump}}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{pump}}}\frac{S_{\mathrm{pump}}}{S_{\mathrm{out}}} = \eta_{o/o}G, \quad \textbf{(1)}$$

where P_{pump} is the incident pump power passing through the pumped faces ($I_{\mathrm{pump}} = P_{\mathrm{pump}}/S_{\mathrm{pump}}$) and P_{out} is the output power through $S_{\mathrm{out}}(I_{\mathrm{out}} = P_{\mathrm{out}}/S_{\mathrm{out}})$.

When LCs are illuminated by sunlight, they receive a uniform irradiance over the whole exposed area. However, in the case of LED pumping, the incident pump lighting is nonuniform and composed of multiple light spots. Therefore, to take this into account, we introduce a parameter η_{fill} to obtain a new definition for the concentration factor C_{LED},

$$C_{\mathrm{LED}} = \eta_{o/o}\eta_{\mathrm{fill}}G, \quad \textbf{(2)}$$

where η_{fill} is the filling factor of the pumped surface by LEDs and defined as

$$\eta_{\mathrm{fill}} = \#\,\mathrm{of\ LEDs}\frac{S_{\mathrm{LED}}}{S_{\mathrm{pump}}}, \quad \textbf{(3)}$$

where S_{LED} is the emitting surface of one LED ($1\ \mathrm{mm}^2$ in our case).

Thus, the light concentration ratio C_{LED} can be defined as the ratio of the output irradiance (in $\mathrm{W/cm^2}$) to the irradiance of one LED. Equation (2) shows that in order to maximize C_{LED}, the pump surface has to be as large as possible. In the case of a slab, it means that both faces (top and bottom) should be used and filled by LEDs.

The filling factor also plays the following key role: the LED packaging has to be optimized and the space between LEDs reduced to a value as low as possible. In case of a slab with double side pumping, the ratio $S_{\mathrm{pump}}/S_{\mathrm{out}}$ can be simply expressed as $S_{\mathrm{pump}}/S_{\mathrm{out}} = 2L/h$. Hence, a high concentration ratio C_{LED} means also a high aspect ratio for the slab. Besides geometrical factors, the optical efficiency $\eta_{o/o}$ of the concentrator also needs to be maximized and can be expressed by

$$\eta_{o/o} = \eta_{\mathrm{exc}}\eta_{\mathrm{PLQY}}\eta_{\mathrm{TIR}}\eta_{\mathrm{extr}}, \quad \textbf{(4)}$$

where η_{exc} is the fraction of the LED power collected by the surface S_{pump} and absorbed by the luminophores, η_{PLQY} is the photoluminescent quantum yield of the luminophore, η_{TIR} is the fraction of the re-emitted light guided by TIR to the edges of the LC, and η_{extr} is the extraction efficiency of the concentrator, which is the output power P_{out} divided by the power carried out by all the TIR-guided rays. It is worth noting that η_{extr} is specific to our application since we use only a small part of the edges (S_{out}, see Fig. 1), as opposed to photovoltaic LC using solar cells glued on all of the edge surfaces.

Our LC is a slab of Ce-doped YAG, chosen in virtue of its high photoluminescence quantum yield η_{PLQY} (assumed to be greater than 90% according to [14]) and the relatively good overlap between its absorption band and the emission spectrum of the blue LEDs available in our lab (see Fig. 2). The Ce emission band is in the yellow–red, matching absorption bands of many solid-state lasers like Nd:YAG, $Nd:YVO_4$, ruby, Ti:sapphire, or alexandrite.

Our slab dimensions are 100 mm × 9 mm × 1 mm ($L \times l \times h$, corresponding to a geometrical concentration factor $G = 200$). The thickness of the LC (1 mm) was chosen to optimize the LED absorption (and hence the η_{exc} ratio) for the doping concentration of the Ce ions of our sample (between 0.2% and 0.3%). For LEDs with the spectrum shown in Fig. 2, the pump absorption is about 80%.

We can observe in Fig. 2 that the overlap between the Ce:YAG absorption and emission spectra is very small, meaning that the reabsorption losses are very low for the light emitted by Ce^{3+} ions. In addition, YAG is a well-known material whose growing process has been optimized for years; this guarantees low internal losses (measured at $1.62 \times 10^{-2}\ \mathrm{cm}^{-1}$ in our sample). These properties help to maximize η_{extr}.

Because of the Ce:YAG high refractive index (typically 1.83 in the visible), the escape cone here has a much smaller aperture than typical polymer or glass LCs, then maximizing η_{TIR}:84% (for an emission centered at 550 nm) compared to 70%–75% for polymers.

However, this advantage becomes a drawback when one needs to extract the light on the edge surface. In order to lower this effect and increase η_{extr}, one solution is to frustrate the TIR on the output surface by bonding the LC directly on the laser crystal, the intermediate glue having a refractive index much higher than the air.

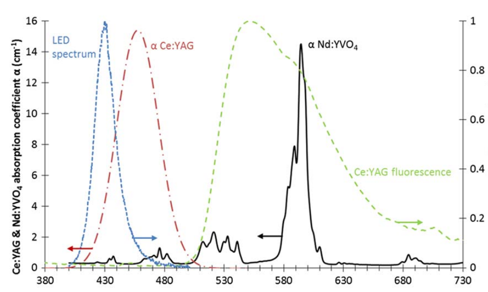

Fig. 2. Ce:YAG (red), $Nd:YVO_4$ absorption coefficient (average of c and a axes, black), emission spectra of Ce:YAG (green), and LED in the pulsed regime (100 μs, 4 A, 10 Hz, room temperature, blue).

As the laser medium we chose a $Nd:YVO_4$ crystal presenting an absorption band matching the Ce:YAG emission in the yellow range (Fig. 2). Moreover, $Nd:YVO_4$ is a well-known crystal with low losses and a high "emission cross section × lifetime" product leading to high gains and low thresholds for laser oscillators.

The $Nd:YVO_4$ laser crystal is an a-cut 20-mm-long crystal with a doping concentration of 1 at. % and a 2 mm × 2 mm square section. The crystal is oriented to maximize the absorption (pumping along *a* and *c* axes). The doping concentration is chosen as high as possible while avoiding concentration quenching [15]. A transverse face (20 mm × 2 mm) is polished for the pumping but is not antireflection (AR)-coated. One of the crystal laser facets is high-reflective coated at 1064 nm, while the other facet is AR-coated with a reflectivity below 0.1% at 1064 nm.

The LED arrays are custom made to ensure a high LED density over a large area. An LED array consists of a matrix of 5 × 5 chips of 1 mm^2 each (Fig. 3). A total of 350 LEDs are used on either side of the concentrator and distributed in 14 arrays. The LEDs are close coupled to the LC whose width (9 mm) is chosen to match the LED array dimensions. Each chip is separated from one another by a 0.3 mm gap in one direction and a 0.8 mm gap in the other direction (illustrated in the inset of Fig. 3). In our case, the filling factor η_{fill} is 19.4%.

In the continuous wave regime, each LED emits 1 W for a driving current of 1 A. To increase the emitted power, we operate the LEDs in the pulsed regime. We design and make a specific electronic driver delivering square current pulses with a duration of 100 μs (matching the $Nd:YVO_4$ lifetime). The output spectra do not show much variation between continuous and pulsed operation. We operate the LEDs at 3.75 A, far below the breakdown current at 5 A. At this current, each chip emits an output power of 1.9 W, corresponding to an irradiance of 190 W/cm^2. Thus, the maximal pump power emitted by LEDs is 650 W and the corresponding energy is 65.2 mJ.

The overall setup is given in Fig. 3. We can distinguish the following three main parts in the setup: the pump source, the concentrator, and the laser cavity. We design a plano–concave cavity with an output coupler having a radius of curvature of 500 mm. The cavity length can be adjusted from 50 to 500 mm to optimize the output energy.

Before testing the laser operation, we investigate the concentrator performance. By using a power meter placed at the output edge (with an air gap between the LC and the power meter), we measure an output peak power of 43 W corresponding to an efficiency $\eta_{o/o}$ of 6.6% and a light concentration ratio C_{LED} of 2.6.

Then, the $Nd:YVO_4$ is bonded on the Ce:YAG concentrator by using an UV-curing adhesive (Vitralit VBB1-Gel). The refractive index of the glue is between 1.4 and 1.5 by the measurement of the transmission at 633 nm through two YAG crystals, with or without glue. The power coupled in the $Nd:YVO_4$ cannot be measured directly once it is glued to the Ce:YAG. Therefore, we use ray-tracing software (LightTools) to estimate this value. Upon taking into account the Ce:YAG losses (measured at $1.62 \times 10^{-2}\ \mathrm{cm}^{-1}$) and the refractive index of the glue, we calculate that the performances are considerably improved; the output peak power coupled into the $Nd:YVO_4$ reaches 165 W, that is to say a pump energy of 16.5 mJ, an optical efficiency $\eta_{o/o}$ of 25.2%, and a light concentration ratio C_{LED} of 10. Ray tracing simulation shows that the concentration ratio C_{LED} can be improved up to 18 ($\eta_{o/o}$ up to 46.3%), assuming that the glue has exactly the same refractive index as both the LC and the laser crystal and that all of the propagation losses are negligible. The different configurations and important values are gathered in Table 1.

For laser operation, the LEDs are driven at a 100 Hz repetition rate to limit the thermal effects on the uncooled crystals. Hence, the average pump power is only 6.5 W incident on Ce:YAG and 1.65 W on the $Nd:YVO_4$ crystal.

The laser oscillation threshold is reached for a Ce:YAG pump energy of approximately 4 mJ. We measure the performance of our system for different transmissions of the output coupler (Fig. 4). Our best results are obtained with a 3% transmission output coupler. The output energy is then 360 μJ at 1064 nm for a Ce:YAG energy launched in the $Nd:YVO_4$ estimated to be 16.5 mJ. This corresponds to an optical efficiency of 2.2% and 0.6% related to the total energy emitted by the LED arrays.

Following the spectral overlap (between LED spectrum and the averaged absorption spectra for the *c* and *a* axes) and the doping concentration of the vanadate, we calculate an absorption of 36%. As expected by the transverse pumping configuration and the low absorption, the laser profile is highly multimodal, filling the crystal aperture (inset of Fig. 4).

Subsequently, to explore the maximal gain available, we progressively increase the transmission of the output coupler and measure the pump energy required to reach the laser threshold. From these measurements, we deduce the single-pass small-signal-gain G_0 and plot it versus the pump energy (Fig. 4). This gain reaches up to 1.13. Above 5%, one can observe an inflection in the gain curve certainly related to thermal effects; since the $Nd:YVO_4$ is not cooled, the pumping induces an increase of the crystal temperature and consequently a decrease of the emission cross section [16].

Extending the pumping duration to 3 ms at a 5 Hz repetition rate is also allowed by our electronic driver. In this configuration, we obtain 8.5 mJ of laser energy for an input energy estimated at 500 mJ from the concentrator and 2 J from the LED arrays. This result corresponds to an optical efficiency of 1.7% and 0.4% related to the total energy emitted by the LED arrays. We attribute these lower efficiencies, compared to short pulse pumping, to a higher thermal load in the gain medium.

Despite a slightly different pumping scheme compared to the Nd:Ce:YAG laser demonstrated by Villars *et al.* [8] (which is the

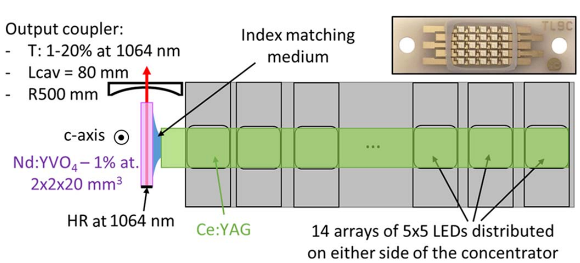

Fig. 3. Overall setup of the experiment. Inset: illustration of an LED array.

Table 1. Comparison of the LC's Performance for Various Index Matching Media[a]

Configuration	P_{out} (W)	C_{LED}	$\eta_{o/o}$ (%)
Air	43	2.6	6.6
Adhesive	165	10	25.2
Ideal case	300	18	46.3

[a]Ideal case (no losses, identical refraction indices for LC, optical adhesive and gain medium).

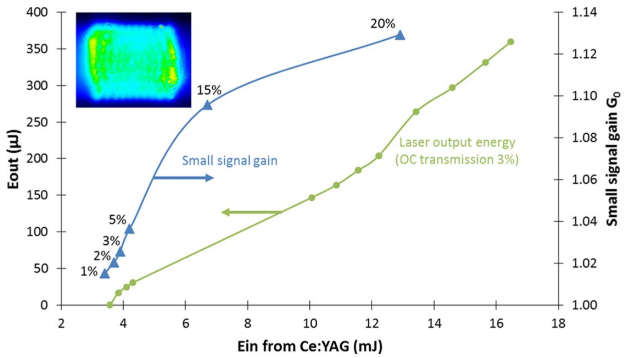

Fig. 4. Evolution of the output energy from a 3% transmission output coupler (with an optical adhesive between the Ce:YAG and the $Nd:YVO_4$) and the small-signal gain for different transmissions of output coupler, as a function of the output energy from the concentrator. Inset: spatial profile of the laser beam at a pump energy of 16.5 mJ.

latest published result to our knowledge), we obtained a lower optical efficiency (0.6% compared to 6.2%). This is mainly due to a better energy transfer from Ce to Nd in the case of a co-doped crystal. In our case, the energy transfer is achieved by emission and absorption processes and the spectral bands of Ce and Nd are not perfectly overlapped.

Consequently, several ways exist for improvement. The first one consists in using a concentrator doped with luminophores having a narrower emission spectrum, like quantum dots [17], with better matching of the narrow lines of Nd crystals. The second one consists in choosing laser crystals with larger absorption bands in the yellow range; ruby, alexandrite, or Ti:sapphire are good candidates for spectral matching with Ce:YAG.

Using a concentrator as an intermediate between LED and laser medium presents, however, many advantages. Our results show a laser threshold 15–40 times lower than in [8], resulting from the combination of the higher emission cross section of $Nd:YVO_4$ over Nd:YAG at 1064 nm and the concentration effect that allowed a pump irradiance at the concentrator output as high as 1830 W/cm^2, typically one order of magnitude higher than the irradiance available in direct LED pumping [8].

We believe that the pump irradiance and the corresponding concentration ratio are far from maximum. $\eta_{o/o}$ can be improved by a better index matching between the concentrator and the laser medium or even by additive free bonding between the two crystals. The filling factor can be easily increased in our setup: we used only 14 arrays compared to a potential of 20 arrays according to the dimensions of our Ce:YAG. It can also be improved by more compact LED packaging flip-chip technology [18]. Moreover, the aspect ratio L/h can be increased by several methods: LEDs with an emission spectrum shifted toward 450 nm lead to a lower absorption length in Ce:YAG. Consequently slabs with a lower thickness h could be used (500 μm is mechanically possible for a length L of 100 mm in a single crystal). To increase L, one could also bond Ce:YAG crystals together. Our calculations show that the concentration ratio increases by a factor 1.6 when two crystals of 100 mm are bonded (assuming losses as low as 1.62×10^{-2} cm^{-1}). Finally, we can also recycle the output light on the other edge of the concentrator with a mirror.

The other advantage of LED-pumped concentrators compared to direct LED pumping is power scaling. Indeed, the transverse surface of a laser crystal is limited to a few tens of cm^2 (14 cm^2 in [8]), clamping the LED pump power to a few hundred of watts (322 W [8]). In our Ce:YAG concentrator, the pump surface is 18 cm^2 with an LED pump power of 650 W and, despite the unoptimized conversion efficiency ($\eta_{o/o} = 25.2\%$) of the concentrator, the converted pump power launched in the laser medium already reached 165 W. Instead of covering the crystal surface by LEDs, it can be covered by the output edge of concentrators. As we obtain a concentration ratio C_{LED} of 10, it means that a laser crystal can be (at least) LED pumped with a power 10 times higher, thanks to concentrators.

In conclusion, we demonstrated for the first time a high-power LED-pumped Ce:YAG concentrator. It emits 165 W of peak power with an irradiance reaching 1830 W/cm^2 and an optical efficiency of 25.2%. This Letter also reports, to the best of our knowledge the first solid-state laser ($Nd:YVO_4$) pumped by an LED concentrator. Operating with pump pulses of 100 μs at 100 Hz, the laser produces an energy of 360 μJ at 1064 nm. The corresponding optical efficiency is about 2.2% with respect to the concentrator output (6% related to the absorbed energy) and 0.6% with respect to the LED pump energy.

As LED lighting is a very active and growing market, constantly improving the LED performance and reducing the cost per watt, LED-pumped concentrators open the way for high-power, low-cost, solid-state lasers tunable in the red-near-infrared, such as Ti:sapphire.

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